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The streamflow hydrology of glacierized watersheds: a brief overview

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Outline

1 Elements of a glacial watershed

2 Glacier hydrology & hydraulics

3 Glacial river characteristics

- 3a Water quantity
- 3b Water quality & hydroecology

4 Catastrophic glaciohydrologic events

5 Streamflow modelling for glacial watersheds

6 Hydroclimatology of glacial river flows

- 5a Variability attenuation
- 5b Teleconnections
- 5c Long-term change

7 Summary: why glaciers matter at a watershed scale

Exploring the landscape: elements of a glacial watershed

glacier: persistent ice mass, flowing & sliding under its own weight

roughly U-shaped, glacial-carved valley with abundant sediment

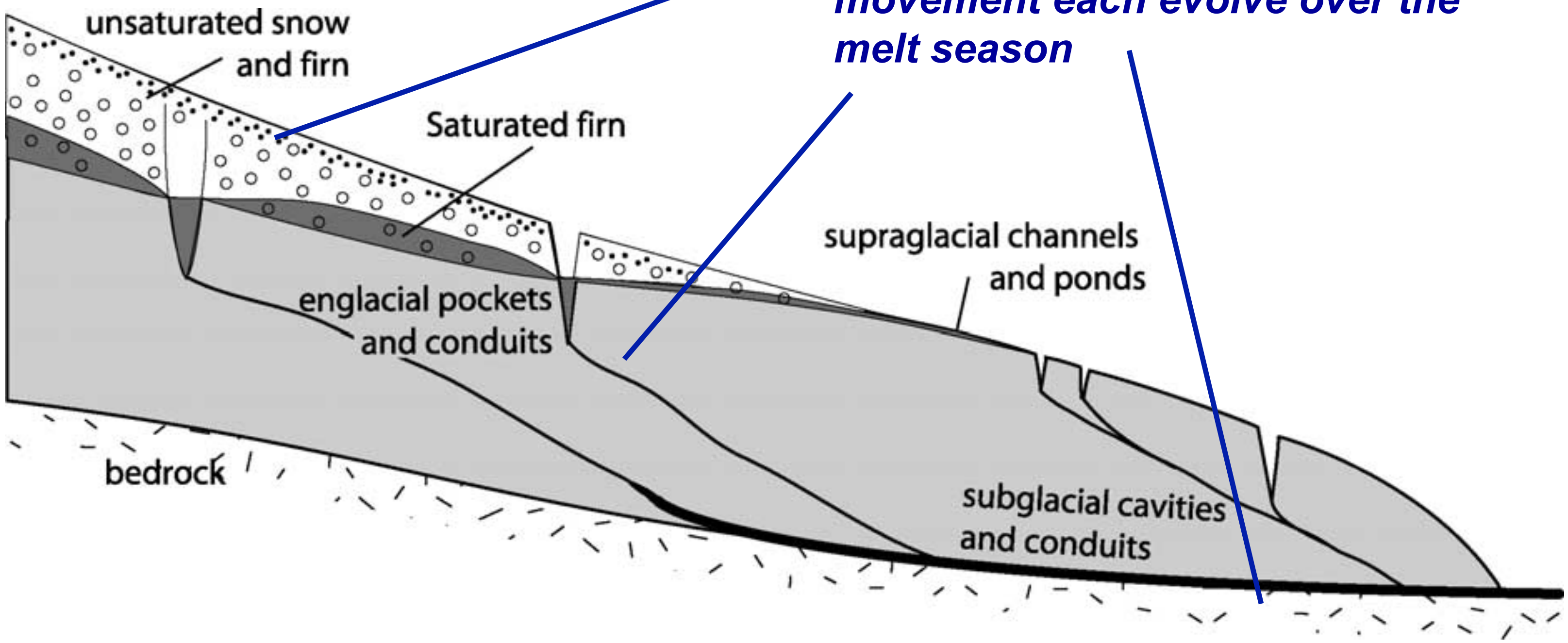
proglacial meltwater stream, typically braided in upper reaches

moraine-dammed lakes common though not universal in headwaters

glacial character progressively less obvious moving downstream

image: phys.org/news195839998.html

Taking it from the top: glacier hydrology & hydraulics



Supra-, en-, and sub-glacial mechanisms for water storage and movement each evolve over the melt season

image: Jansson et al., *J. Hydrol.*, 2003

- Powerfully influences glacier dynamics, e.g., surges
- Affects downstream hydrograph: diurnal timing, seasonal shifts

A river runs (from) it: basic streamflow properties of glacial watersheds

Some "typical" hydrologic features of glacier-fed rivers:

- Higher water resource productivity – can be as important as area
- Higher-amplitude seasonal cycle
- Later seasonal peak
- Higher late-summer and autumn flows
- Essentially driven by the additional source of melt in a glacial watershed

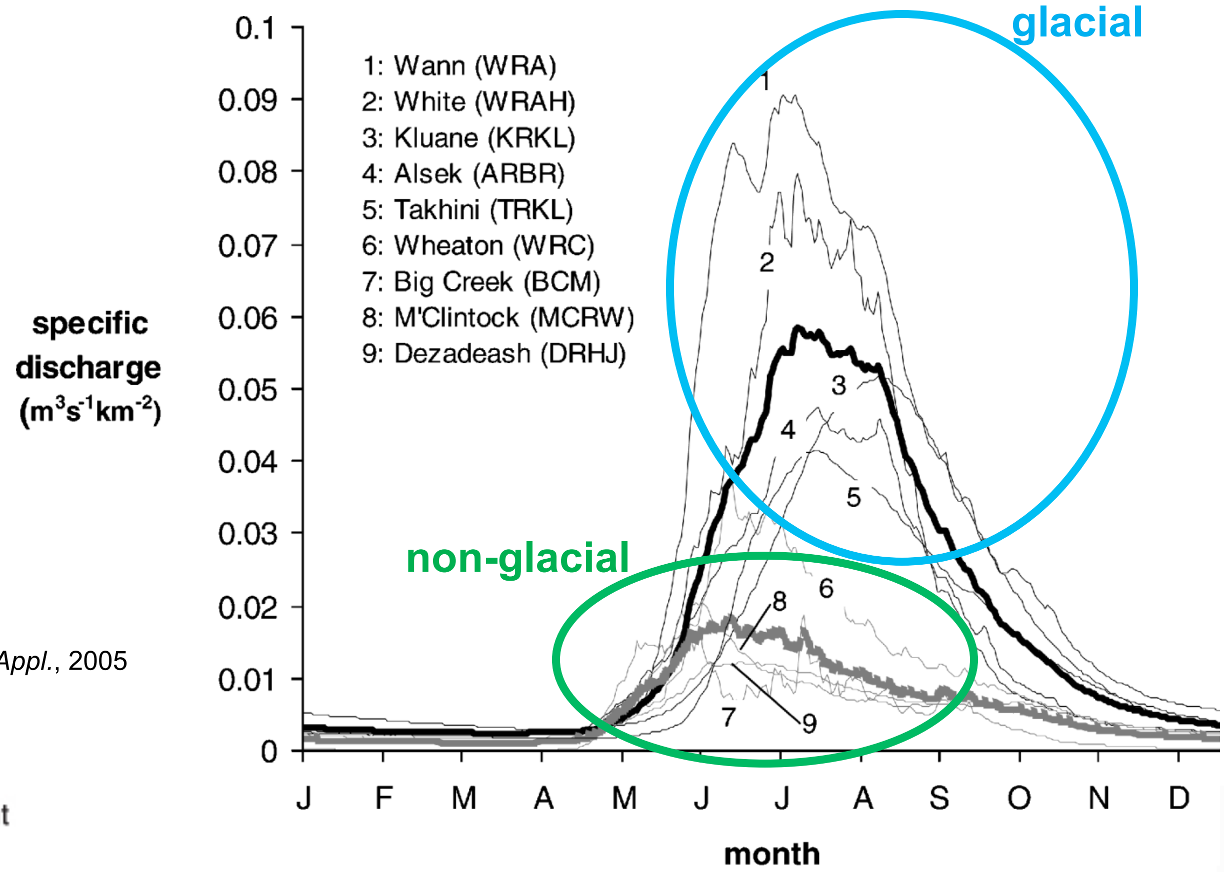


image: Fleming, *River Res. and Appl.*, 2005

Do critters like glaciers? Water quality & ecology

Some “typical” water quality features of glacier-fed rivers:

- Higher sediment load, turbidity
- Lower water temperatures, especially toward late summer after seasonal snowpack depleted

Hydroecological characteristics:

- Flow and water quality characteristics: distinct ecosystem type (“kryal”)
- Turbidity & channel instability: impoverished ecosystem with respect to invertebrates
- Cooler temperatures & higher flows in late summer-autumn: may be beneficial to salmon (cold stenotherms, migration/spawning habitat), especially if upstream lakes trap sediment

Oops! (Glacier-related catastrophic hydrologic events)

- Glacial outburst floods (jökulhlaups):
  - Failure of ice- (or moraine-) dammed lakes
  - Relatively common in Iceland; and BC-Alaska-Yukon border areas
  - Juneau is bracketed by rivers that do this (Tulsequah/Taku; Mendenhall)
- Debris torrents (~channelized landslides):
  - Glacial terrain susceptible: steep; loose sediment; glacial debuttressing

hydrograph for 1997 Taku outburst flood

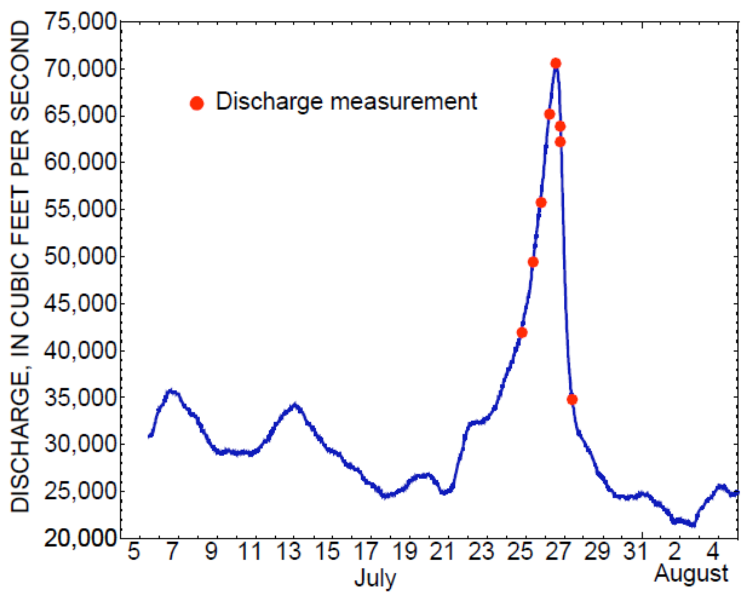


image: ak.water.usgs.gov/Publications/Factsheets/tulsequahlake.pdf

Capricorn glacier/Mount Meager landslide

image: thetyee.ca/News/2010/08/12/MeagerLandslide/

Virtual watersheds – streamflow models for glacial rivers

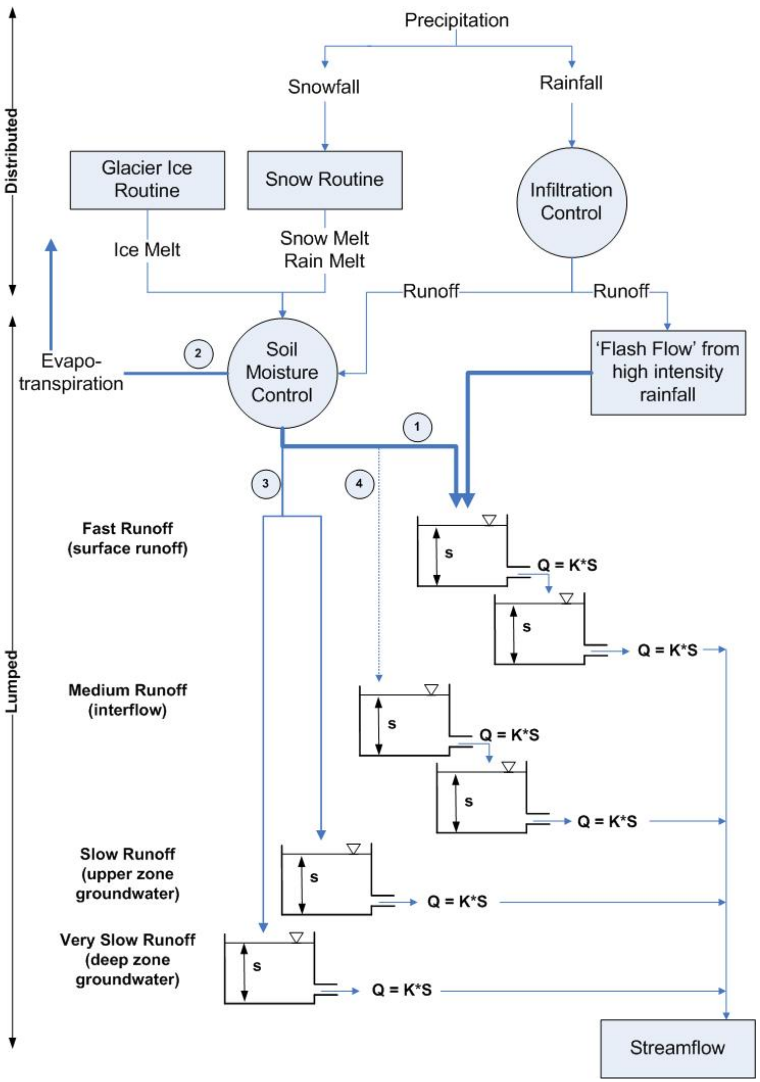
What is a streamflow (hydrological, watershed, rainfall-runoff) model?

- Mathematical-computational model converting weather to river discharge
- Large number of individually complex, often nonlinear, physical & biological processes across the watershed
- Used for water supply or flood forecasting, EAs, habitat & fisheries studies, reservoir management, fundamental science, etc

How do streamflow models incorporate glacial melt generation?

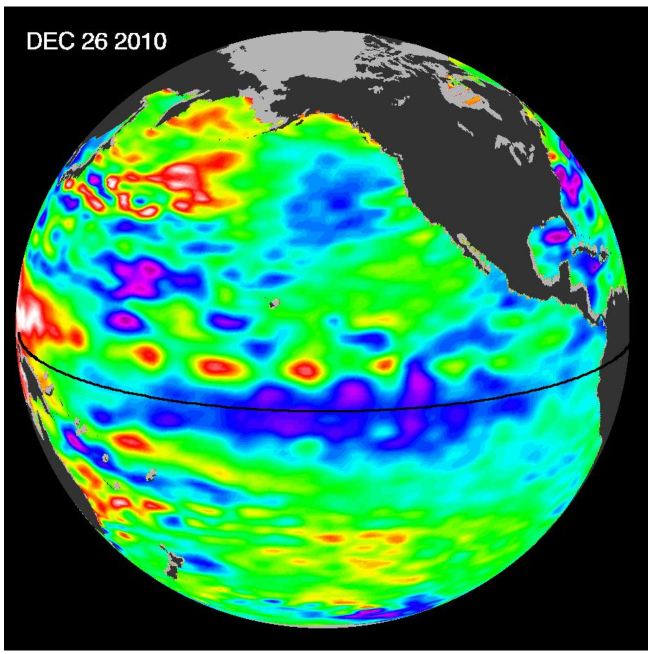
- Most don't: seasonal snowpack only
- Those that do, generally use very simple parameterizations

Example: UBC Watershed Model



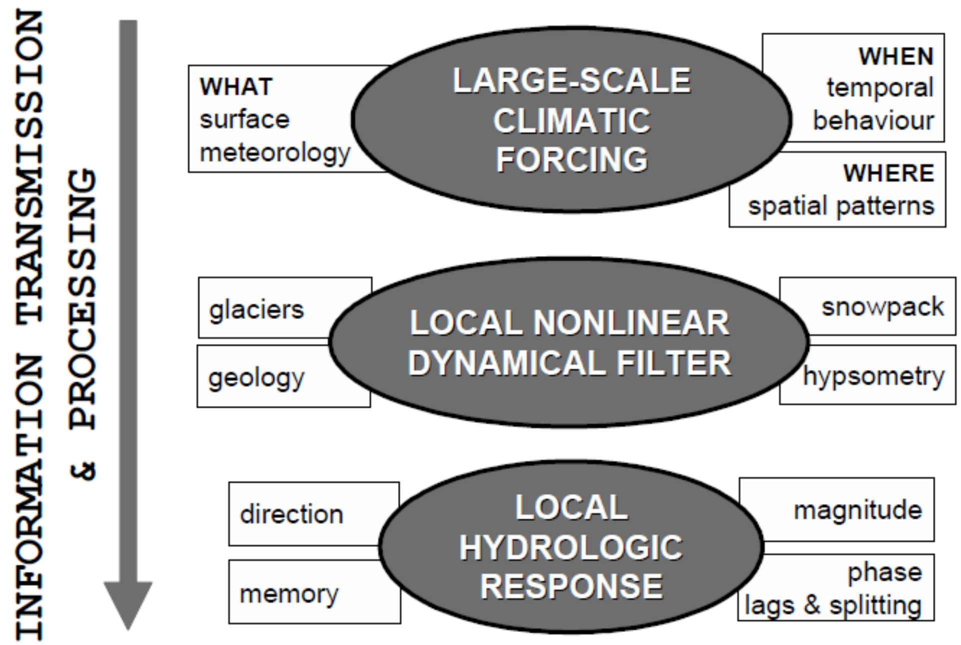
The only constant is change: the hydroclimatology of glacier-fed rivers

- Significant body of evidence has emerged, much of it only over the last decade, that glacial cover substantially modifies downstream flow responses
- Provide here a few examples, organized by timescale



One form of climate variability: El Niño-Southern Oscillation (2010-11 La Niña shown)

image: NASA/JPL-Caltech



Conceptual model for modification of climate response by local-scale terrestrial hydrologic characteristics – especially glaciers

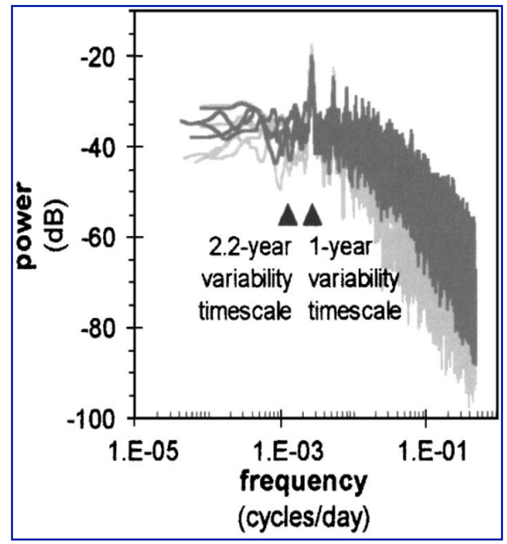
Glacially damped streamflow variability

- Has been known since at least Henshaw, *Trans. AGU*, 1933 that watershed glacierization can attenuate year-to-year variability in river flow
- High-snowpack year: lower-albedo, higher-productivity ice covered longer
- Low-snowpack year: lower-albedo, higher-productivity ice uncovered sooner
- Operative timescales may be short, not all flow indicators affected, may reverse at very high glacial cover

Table 1. Coefficients of Variation Analysis Results

	q_{min}	q_{med}	q_{mean}	q_{max}	q_{IQR}	v_T	t_C	t_{max}
WRC	11.0	15.4	12.7	14.3	20.0	12.5	3.1	7.1
MCRW	13.3	23.6	11.6	27.0	28.2	11.6	4.2	3.6
DRHJ	20.2	14.8	15.6	24.7	32.2	16.7	3.1	7.7
BCM	63.2	36.5	24.0	29.2	38.1	22.6	6.6	15.9
TRKL$^{(G)}$	11.7	17.1	6.9	17.0	18.0	6.9	0.9	3.0
WRAH$^{(G)}$	9.9	17.3	12.9	12.1	21.0	11.9	2.5	9.0
KRKL$^{(G)}$	33.0	13.7	9.1	10.9	20.2	9.2	1.8	2.4
ARBR$^{(G)}$	12.9	21.6	10.2	14.8	16.4	7.9	1.0	6.2
WRA$^{(G)}$	11.4	24.6	8.8	15.7	17.6	8.8	1.5	6.0
R_S[a]	−0.28	0.08	−0.64	−0.55	−0.73	−0.71	−0.77	−0.37
p[b]	0.250	>0.250	0.050	0.100	0.025	0.025	0.025	0.250

Note: (G) indicates glacial river; full names given in Fig. 1. Degree of glacierization increases downward through table.
[a]R_S=Spearman correlation coefficient.
[b]p=probability of Type I error.



images: Fleming & Clarke, *ASCE J. Hydraul. Eng.*, 2005

Glacier-modulated responses to climate modes: opposite teleconnections (ENSO in Alberta)

image: Lafrenière and Sharp, *Hydrol. Proc.*, 2003

	1996–97	1997–98	1998–99	1999–2000
Snowpack (mm SWE) at Bow Summit (2080 m a.s.l.)				
30 March	462	257	460	434
30 May	254	0	329	239
Exhaustion of snowpack at Bow Lake met. station (1940 m a.s.l.)	—	2 May	30 May	23 May
Discharge (10^6 m^3)				
Bow River (7 June–31 August)	7·7	4·1	8·1	7·5
June	3·5	1·9	2·9	2·5
July	2·7	1·8	3·5	3·6
August	1·5	0·9	1·8	1·4
Glacial (7 June–31 August)	28	34	20	19
June	9·0	5·3	3·5	2·7
July	9·3	15	6·7	8·9
August	9·4	13	9·5	7·1

lightly glacierized

heavily glacierized

- 1997-98: strong El Niño event
- Known to produce drier winters, lower snowpack in Canadian Rockies
- Snowmelt & non-glacial river flow
- Glacier melt & glacial river flow

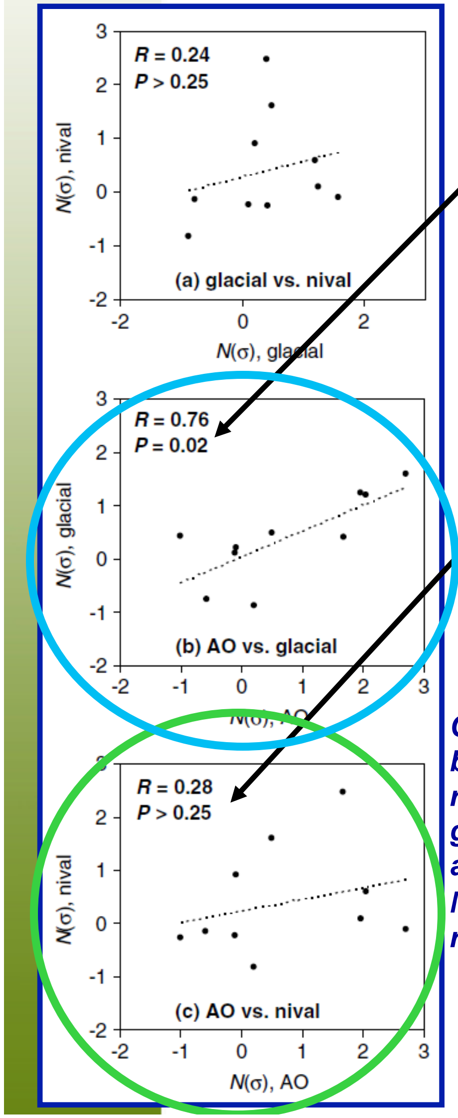
Glacier-modulated responses to climate modes: selective teleconnectivity (AO in Yukon)

images: Fleming et al., *Int. J. Clim.*, 2006

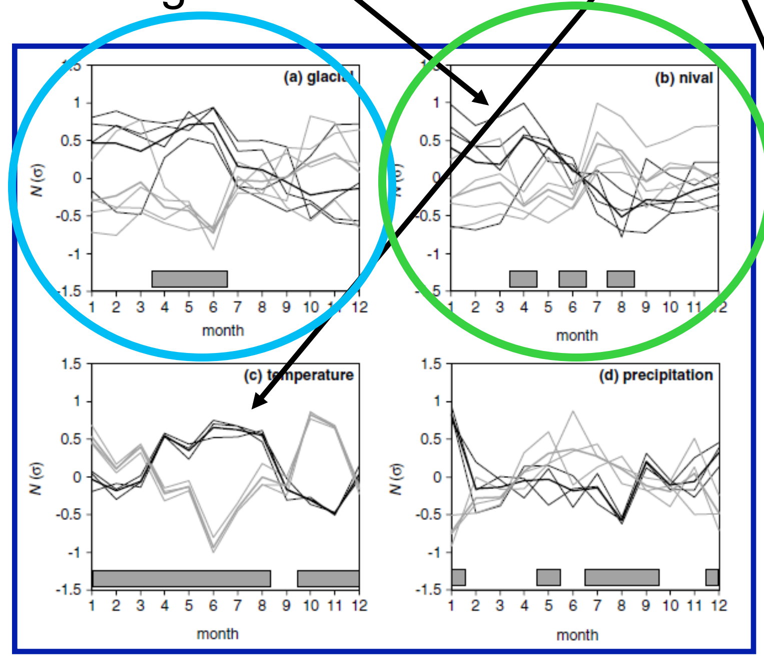
glacial rivers show significant
net annual water resource response to the Arctic Oscillation

nival rivers do not: only a freshet timing shift

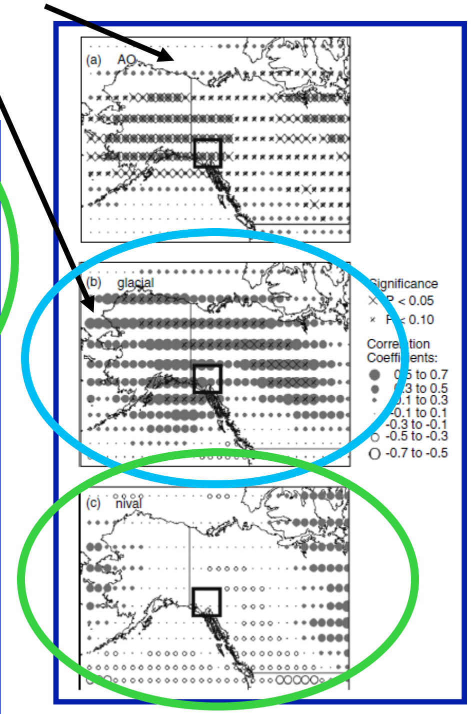
presence/absence of glacial ice reservoir potentially available for melting ↔ spring-summer *T* anomalies & SLP conditions



Correlation between PCA-regionalized glacial & nival annual flows by Monte Carlo randomization



Composite WSC & AHCCD analyses by Mann-Whitney



NCEP Apr-Jun SLP point correlation maps

Long-term climatic change, glaciers, and streamflow: conceptual considerations

- Mountain glaciers receding since end of LIA, broadly speaking
- Mass loss thought to be accelerating under anthropogenic climate change
- How does this affect long-term downstream flow trends?
- General pattern: evolutionary timeline characterized by interval of river flow increase, followed by decrease

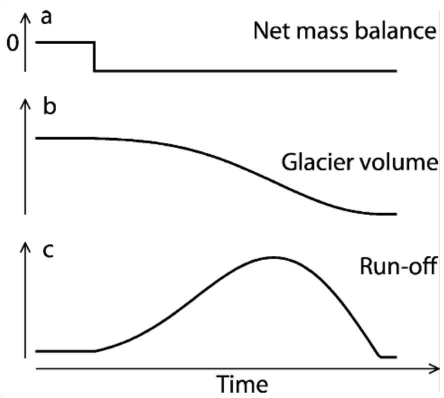


image: Jannson et al., *J. Hydrol.*, 2003

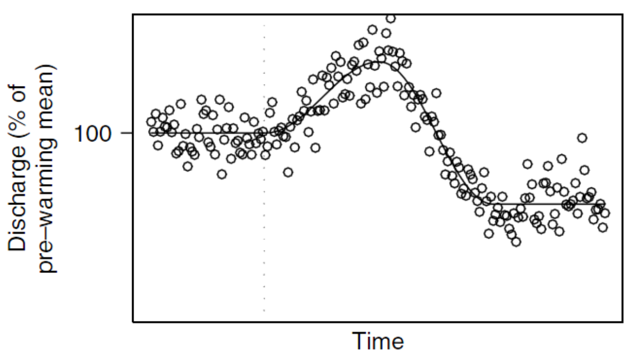


image: Moore et al., *Hydrol. Proc.*, 2009

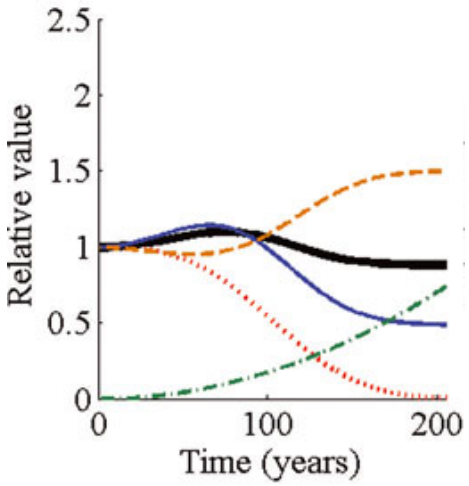


image: Baraer et al., *J. Glac.*, 2012

Long-term climatic change, glaciers, and streamflow: what's actually happened on the ground

- Different – even opposite – flow trends between glacial & non-glacial rivers
- Effects most acute in late summer
- Glacial river trend direction depends on region: space-for-time substitution?

Coast, Rockies

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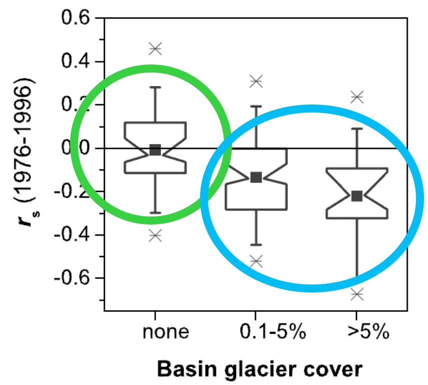

image: Stahl & Moore, *Water Resour. Res.*, 2006

REGION	PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	yr
south coastal	SCA	0.7	1.9	2.1	1.9	-1.3	-0.1	0.3	0.8	1.1	0.8	0.0	0.2	0.7
	CMX	0.4	0.7	0.9	0.9	-0.7	0.1	0.4	0.4	0.4	0.3	0.0	0.1	0.3
	ASH	0.2	0.1	0.4	0.4	-0.6	-0.1	-0.1	0.0	0.0	0.2	0.1	0.1	0.0
	JOR	0.2	0.0	0.5	0.6	-0.3	0.4	-0.1	-0.2	0.0	0.0	0.0	0.1	0.1
	ALU	0.3	-0.1	0.7	0.4	-0.3	0.5	-0.1	-0.2	0.1	0.2	0.1	0.1	0.2
	CQD	0.2	-0.1	0.7	0.5	-0.3	0.4	0.0	-0.1	0.2	0.2	0.1	0.1	0.2
	SFL	1.0	0.0	3.5	2.4	-1.6	1.8	-0.1	-0.2	0.5	0.8	0.4	0.2	0.7
	WAH	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	COM	0.4	0.4	0.9	0.7	-0.5	0.2	0.1	-0.1	0.3	0.7	[illegible]	0.2	0.3
	CMS	0.2	0.4	0.7	0.7	-0.3	-0.1	0.0	-0.3	-0.2	-0.1	-0.5	-0.1	0.0
Bridge	BRR	0.0	0.1	0.3	0.1	-0.1	-0.1	0.0	0.1	0.9	0.9	-0.3	0.2	0.2
	LAJ	-0.3	0.0	0.1	0.1	0.1	0.0	0.1	0.3	0.7	0.7	-0.7	0.4	0.1
Columbia	MCD	3.7	1.3	1.8	1.7	0.9	0.9	0.7	-0.1	1.1	7.3	-5.1	0.0	1.2
	REV	1.5	0.0	-0.1	0.7	-0.2	-0.1	0.1	0.9	1.7	3.4	-0.9	[illegible]	0.6
	ARD	2.1	0.3	1.5	1.7	0.9	1.4	-0.4	2.0	0.5	0.0	-2.0	[illegible]	0.7
	WGS	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.1
	SGR	0.5	0.2	0.2	0.3	0.2	0.1	-0.1	0.1	0.5	-0.3	-0.3	0.0	0.1
Kootenays	DDM	1.2	0.3	0.0	0.2	0.1	0.1	0.1	0.9	0.2	1.5	[illegible]	0.9	0.4
	KLK	1.7	-0.8	2.1	3.0	1.1	3.3	-1.8	4.1	3.5	1.4	0.1	[illegible]	1.5
Peace	GMS	-1.6	0.5	0.2	-0.4	2.0	0.4	2.4	-3.1	22.2	-2.3	1.4	[illegible]	2.0
combined usable inflow	n/a	9.6	7.1	14.6	14.2	1.1	6.2	4.0	-0.8	39.7	21.2	-14.6	1.7	8.7

image: Fleming & Weber, *J. Hydrol.*, 2012

St. Elias, Alps

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Table 2. Trend estimation results [10^{-3} yr^{-1}]. Glacierized catchments are listed from left to right in order of increasing degree of glacial cover.

Metric	Glacierized Basins					Nonglacierized Basins			
	TRKL	WRAH	KRKL	ARBR	WRA	WRC	MCRW	DRHJ	BCM
V_T	1.5	0.9	3.7	2.3	5.5	−0.8	−0.4	−1.4	−4.3

image: Fleming & Clarke, *Can. Water Resour. J.*, 2003

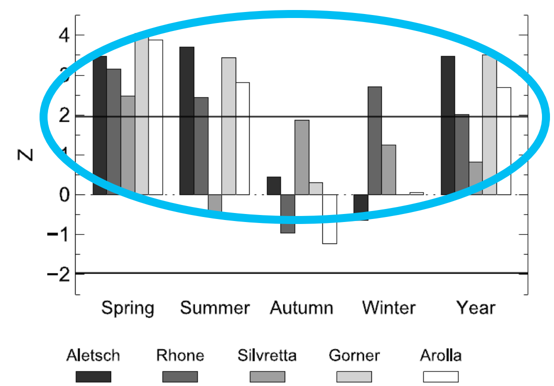
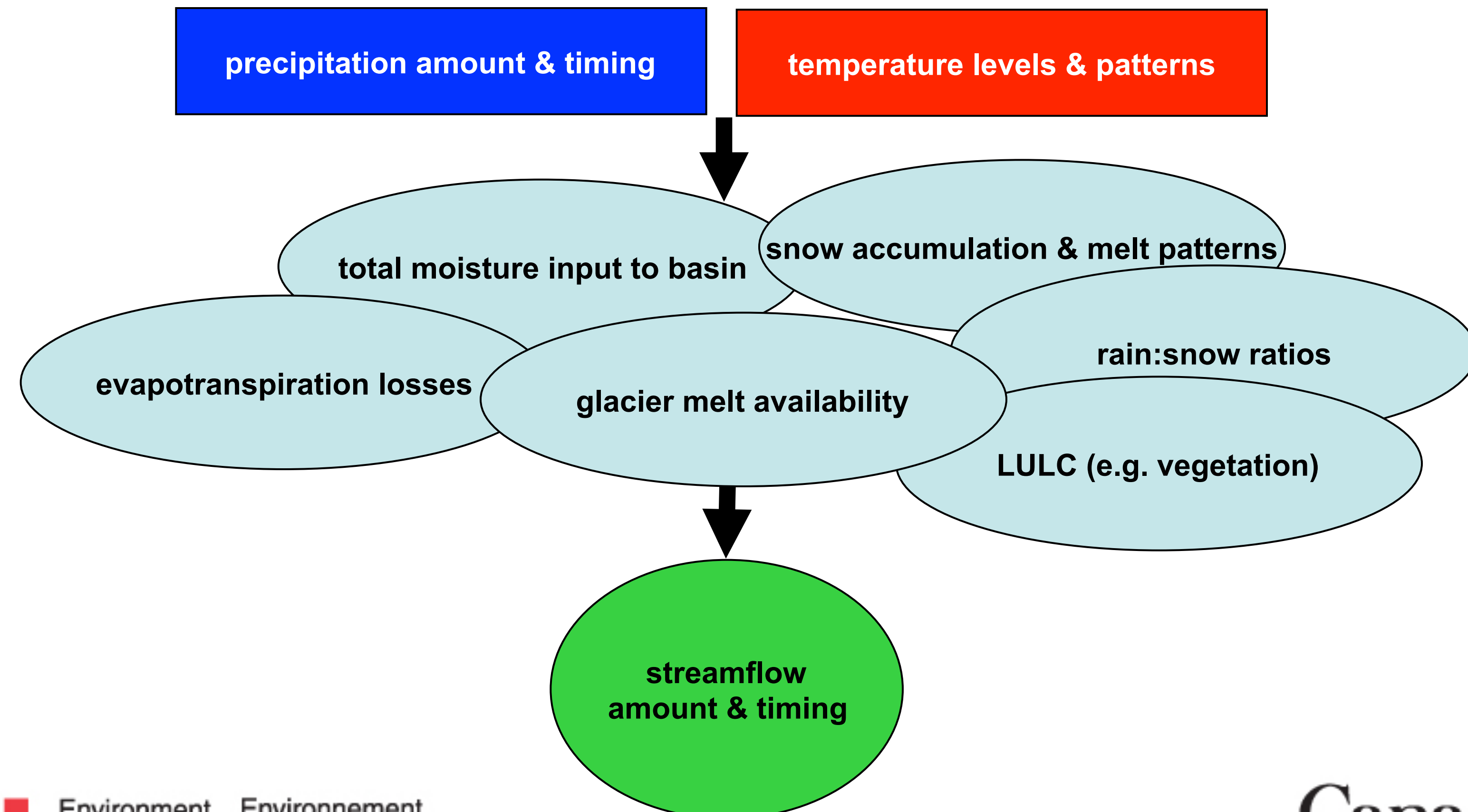


image: Pellicciotti et al., *Water Resour. Res.*, 2010

Long-term climatic change, glaciers, and streamflow: exploring possible futures

- What will be the effects of potential future climatic changes on river flows?
- Multi-faceted problem
- Glaciers, and glacial responses to future climate, are an important element



Long-term climatic change, glaciers, and streamflow: exploring possible futures

- Long modelling chain involved
- Glacier change adds another step
- Relatively few studies to date have tackled the full problem

EMISSIONS SCENARIOS (SRES)

- Projections of future GHG inputs to atmosphere
- Scenarios of 21st century global socioeconomic activity
- Many different trajectories possible

GENERAL CIRCULATION MODELS (GCMs)

- Process-based models of planetary climate
- Run on massively parallel supercomputers
- Many models; multiple runs (different ICs) for each

DOWNSCALING

- GCMs on too coarse a grid for most watershed studies
- Must “downscale” GCM output to local scales
- Many methods, both statistical & dynamical

MODELS OF GLACIER MASS BALANCE & DYNAMICS

WATERSHED MODELLING

- Feed altered climate into a watershed model
- Produce corresponding streamflows
- Many models available each with uncertain parameters
- Model requires glacial melt module

Long-term climatic change, glaciers, and streamflow: exploring possible futures

- Example: reservoir inflows to Mica dam on the Columbia River (5% glacierized)
- Shown here: CGCM3.1-T47, SRES A1B scenario, $3^{o}C$ warmer, 11% wetter
- Historical glacier loss from Landsat TM, SRTM DEM, aerial photos
- Future glacier area updating used offline UBC EOS dynamical glacier model
- Two statistical downscaling methods used
- Results fed into HBV-EC watershed model

image: BC Hydro

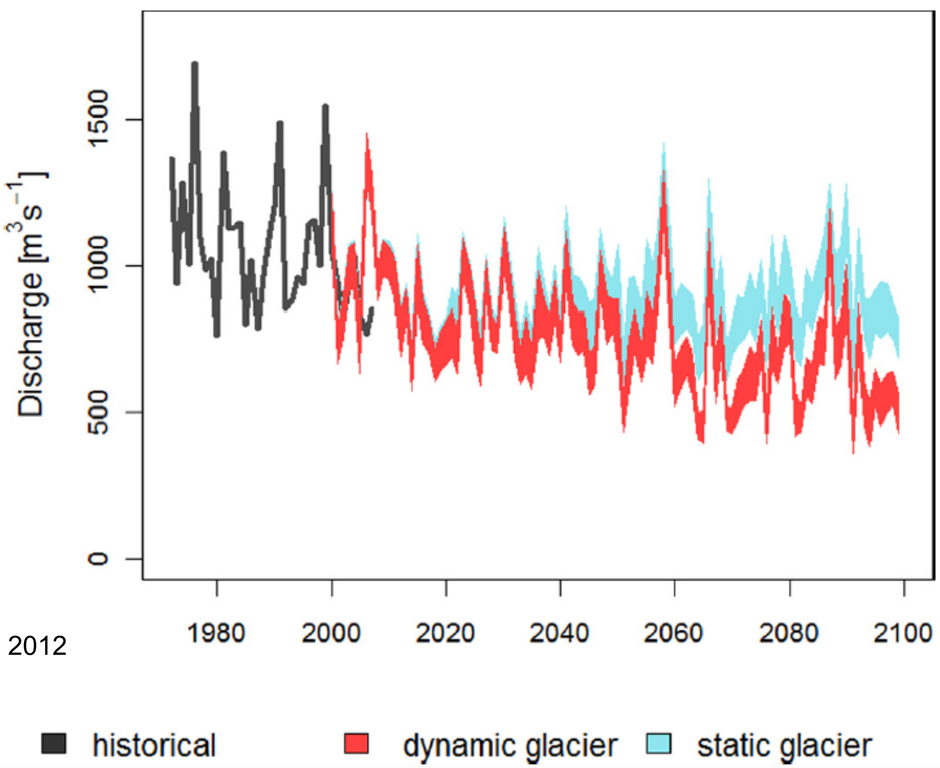


image: Jost et al., *Hydrol. & Earth Sys. Sci.*, 2012

9 reasons why glaciers matter to rivers

1) Major control on timing and magnitude of river flows
2) Major control on water resource productivity
3) Major control on water quality characteristics
4) Flow, turbidity, temperature strongly influence habitat quantity & quality
5) Can be associated with catastrophic hydrologic effects
6) Places specific requirements on process modelling
7) Alters streamflow responses to climate variability & change at all timescales
8) Adjacent glacial & non-glacial rivers can play havoc with regionalization
9) While effects are strongest at the glacial headwaters, even low levels of contemporary glacial cover impart a clear signal at downstream locations

Contact information

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